EARTHQUAKE ENGINEERING AND STRUCTURAL DYNAMICS, VOL. 26, 839–847 (1997)

NEW METHOD FOR SEISMIC ISOLATION OF LIQUID-STORAGE TANKS

PRAVEEN K. MALHOTRA*

Adjunct Faculty, Department of Civil Engineering, California State University, Sacramento, CA 95819-6029, U.S.A.

SUMMARY

Seismic base isolation of ground supported cylindrical liquid-storage tanks is proposed by disconnecting the wall of the tank from the base plate and supporting it on a ring of horizontally flexible bearings; the base plate is supported directly on the ground. The gap between the wall and the base plate is closed with a flexible membrane, which prevents the loss of fluid from the tank and allows the tank wall to move freely in the horizontal direction. The effect of isolation on both the impulsive and the convective (sloshing) responses of the liquid is examined for two steel tanks–one broad and one slender. It is shown that isolation can reduce dramatically the hydrodynamic base shears, overturning moments, and axial compressive stresses in the tank wall without significantly increasing the vertical displacements of the liquid surface due to sloshing. Since the weight supported by the bearings is small compared to the total liquid weight, the bearings in slender tanks experience a net tensile force during strong shaking. © 1997 by John Wiley & Sons, Ltd.

Earthquake Engng. Struct. Dyn., **26**, 839–847 (1997)

No. of Figures: 8. No. of Tables: 0. No. of References: 19.

KEY WORDS: tanks; liquid storage; base isolation; steel; earthquake; seismic; hydrodynamic; sloshing; rubber bearings

INTRODUCTION

Response of ground supported liquid-storage steel tanks to strong ground shaking differs from that of building structures. Ductile response of tanks involves partial uplifting of the base plate—causing yielding at the plate boundary and inelastic stretching of the anchor bolts, if present. Increased flexibility associated with base uplifting reduces the hydrodynamic forces; however, due to reduced contact of the wall with the foundation, the axial compressive stresses in the wall increase—leading, in several cases, to buckling of the wall.[1,2] The plate-shell junction may rupture if subjected to several cycles of large plastic rotations, and the anchor bolts—if not designed to respond in a ductile manner—may suddenly break or slip, causing a sharp increase in base uplift.[3] High stresses in the vicinity of anchor bolts or anchor straps, in poorly detailed connections, may tear the tank wall.[4] Large horizontal forces may overcome friction at the base, causing the tank to slide. An isolation method which provides the benefits of a ductile response without the undesirable effects of wall buckling or tearing, excessive plastic yielding, bolt breaking, and base sliding is therefore highly desirable.

Kelly and Mayes[5] proposed an isolation scheme in which the tank is supported on a large concrete mat which, in turn, is supported on several isolation bearings. Using the same concept, Tajirian[6] reported seismic isolation of a large capacity Liquefied Natural Gas (LNG) tank with rubber bearings, and Zayas and Low[7] reported isolation of a large LNG tank with friction pendulum bearings. Although, suitable for those tanks for which a concrete mat supported above the ground already exists, the above isolation scheme is unsuitable for numerous other tanks that are supported directly on the ground.

Malhotra[8] proposed an isolation scheme in which the tank wall is supported on a ring of vertically soft rubber bearings and the base plate is supported directly on soil. The wall and the base plate are connected to

* Correspondence to: P. K. Malhotra, 4941 Knightswood Way, Granite Bay, CA 95746, U.S.A. E-mail: pmalhotra@aol.com

CCC 0098–8847/97/080839–09$17·50

Received 8 November 1996
Revised 3 March 1997

each other, and are free to lift-off the bearings. The system derives its flexibility from uplifting and rocking of the base, and derives its energy-dissipation capacity from base plate yielding, soil damping, and hysteretic rubber damping. Numerical results showed the ability of the method in reducing significantly the hydrodynamic base moments and axial compressive stresses in the tank wall, while maintaining the values of base uplifts and plastic rotations in the base plate at reasonable levels.

NEW ISOLATION SCHEME

A new isolation scheme is being proposed here in which the wall of the tank is disconnected from the base plate and supported on a ring of horizontally flexible bearings, while the base plate is supported directly on the ground, as shown in Figure 1(a). The challenging aspect of the scheme involves the use of a flexible membrane between the wall and the base plate, which prevents the leakage of fluid from the tank and allows the wall to move freely in the horizontal direction (Figure 1(b)). Since the base plate is unable to prevent the out-of-round deformation of the tank wall near the base, fairly stiff ring beam is needed at the base of the tank wall. The ring beam performs two important functions: (1) It prevents the excitation of relatively flexible out-of-round modes of vibration of the tank-liquid system, and (2) it enables the various bearings to act in unison. One may consider using a concrete ring beam, placed between the tank wall and the bearings.

In this paper, the effect of isolation on both the impulsive and the convective (sloshing) responses of the liquid is examined for horizontal ground shaking only. The effect of vertical shaking is discussed briefly.

SYSTEM MODEL

Fixed-base system

The hydrodynamic effects in a fixed-base tank are evaluated by superposition of these two components: (1) The impulsive component, which represents the action of the liquid that moves rigidly with the flexible tank

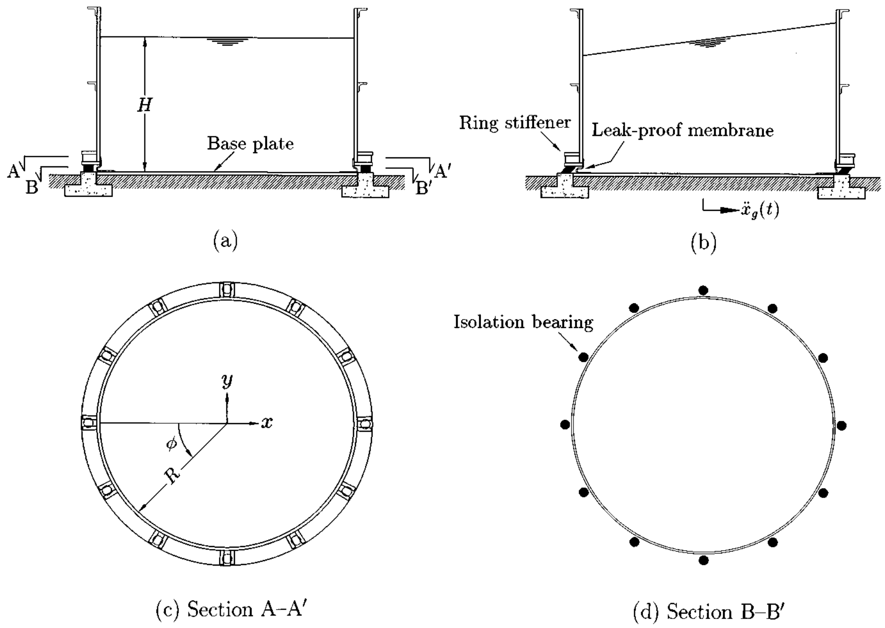

Figure 1. Liquid-storage tank isolated by proposed method

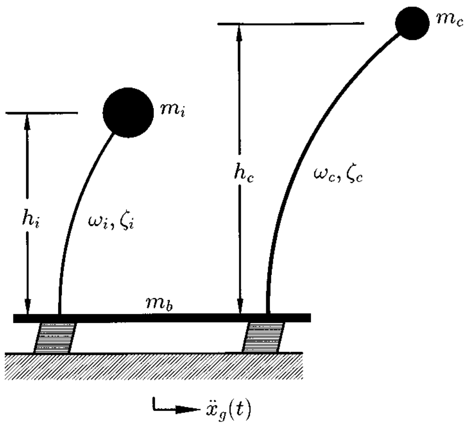

Figure 2. Model of base isolated liquid-storage tank shown in Figure 1

wall, and (2) the convective component, which represents the action of the liquid that experiences convective (sloshing) motion near the free-surface.[9] The impulsive component controls the hydrodynamic pressures, thus the base shears and overturning moments, while the convective component controls the vertical displacements of the free-surface, hence the freeboard requirement. Most tanks are represented adequately by the first impulsive and the first convective mode of vibration, and may, therefore, be modelled by two uncoupled single-degree-freedom systems—one corresponding to the impulsive and the other corresponding to the convective action.

Base-isolated system

The isolated system, shown in Figure 1(a), differs from the fixed-base system in two respects: (1) The wall of the isolated system moves independently of the base plate in the horizontal direction; and (2) the flexible membrane near the base interacts with the liquid in an unknown fashion. The uncoupling of the wall from the plate causes shearing of the liquid near the base, hence the generation of viscous fluid forces and consequently some loss of energy. The loss of energy, however, is negligible for most liquids. Further, since the height of the gap between the base plate and the wall is only a small fraction of the total liquid height, the presence of membrane is not likely to influence the hydrodynamics in the tank in a significant way.

A realistic model for the isolated system may thus be obtained by adding the isolation bearings under the model for the fixed-base system (Figure 2). In this model, the sum of the impulsive and convective masses $m_i + m_c \approx$ the total mass of the liquid plus tank wall; $m_b =$ the mass of the base stiffener assembly; h_i and h_c are the heights of the centroids of the impulsive and convective hydrodynamic wall pressures; ω_i and ω_c the impulsive and convective natural frequencies in rad/s; and ζ_i and ζ_c the impulsive and convective damping ratios. Values of m_i, m_c, h_i, h_c, ω_i and ω_c may be obtained from the published results by Haroun and Housner,[10] or Veletsos and co-workers.[9,11,12] For steel tanks, the impulsive damping ratio is assumed $\zeta_i = 0{\cdot}02$; for water, the convective damping ratio is assumed $\zeta_c = 0{\cdot}005$.

METHOD OF SOLUTION

The equilibrium of x-component of forces on masses m_i, m_c and m_b in Figure 2 gives:

$$m_i \ddot{u}_{ix} + c_i \dot{u}_{ix} - c_i \dot{u}_{bx} + k_i u_{ix} - k_i u_{bx} = -m_i \ddot{x}_g(t) \tag{1a}$$

$$m_c \ddot{u}_{cx} + c_c \dot{u}_{cx} - c_c \dot{u}_{bx} + k_c u_{cx} - k_c u_{bx} = -m_c \ddot{x}_g(t) \tag{1b}$$

$$m_i \ddot{u}_{ix} + m_c \ddot{u}_{cx} + m_b \ddot{u}_{bx} = -[m_i + m_c + m_b]\, \ddot{x}_g(t) - F_{bx}(t) \tag{1c}$$

where, $c_i = 2\zeta_i \omega_i m_i$, $c_c = 2\zeta_c \omega_c m_c$, $k_i = m_i \omega_i^2$, and $k_c = m_c \omega_c^2$; $\ddot{x}_g(t)$ is the x-component of ground acceleration as a function of time t; u_{ix}, u_{cx} and u_{bx} are the displacements of the masses (in x-direction) relative to the ground; the overdot denotes differentiation with respect to time; and $F_{bx}(t)$ is the x-component of the net horizontal force on the base isolation system at time t.

The equilibrium of forces in the y-direction gives an additional set of three differential equations. The solution of all six equations may be obtained using any computer program for the analysis of base isolated buildings, e.g. 3D-BASIS,[13] 3D-BASIS-M.[14] The result presented in this paper were obtained using the latter program.

NUMERICAL RESULTS

The effect of isolation on two steel tanks—one broad and one slender—is examined.

Broad tank

This 27 300 m^3 capacity steel tank has a radius of $R = 24{\cdot}4$ m. It is filled with water to a height of $H = 14{\cdot}6$ m. Its shell thickness varies from 2·9 cm at the base to 0·79 cm at the top. The weight of the tank wall is $W = 3{\cdot}76$ MN, and the mass of the base stiffener assembly $m_b = 25$ tons. Obtained from Veletsos and Tang,[11] for $H/R = 0.6$ and equivalent uniform shell thickness of $h_s = 2{\cdot}03$ cm, the system parameters for the first impulsive mode of vibration are: $m_i = 9630$ tons, $h_i = 5{\cdot}72$ m, and $\omega_i = 24{\cdot}8$ rad/s. Obtained from Veletsos,[9] the modal parameters for the first convective mode of vibration are: $m_c = 16\,600$ tons, $h_c = 7{\cdot}96$ m, and $\omega_c = 0{\cdot}771$ rad/s.

The tank wall is supported on a ring of 60 bearings. The cumulative stiffness of the bearings is 4 MN/m before yielding, and 0·6 MN/m after yielding; the yield deformation is 0·69 cm. Supplemental damping is provided with a series of viscous dampers with one end attached to the ring beam and other to the foundation. The cumulative viscous damping coefficient is 6 MN s/m in both x- and y-directions.

Slender tank

This 1300 m^3 capacity steel tank has a radius of 6·1 m; it is filled with water to a height of 11·3 m. Its shell thickness varies from 0·96 cm at the base to 0·48 cm at the top. The weight of the tank wall is 196 kN, and the mass of the base stiffener assembly is 4 tons. For $H/R = 1{\cdot}85$, and equivalent uniform shell thickness of 0·58 cm, the impulsive system parameters are: $m_i = 912$ tons, $h_i = 5{\cdot}44$ m, and $\omega_i = 40{\cdot}4$ rad/s. The convective system parameters are: $m_c = 323$ tons, $h_c = 7{\cdot}93$ m, and $\omega_c = 1{\cdot}7$ rad/s. The tank wall is supported on 12 bearings with cumulative stiffness of 480 kN/m before yielding, and 72 kN/m after yielding; the yield deformation is 0·69 cm. The cumulative viscous damping coefficient of supplemental dampers is 600 kN s/m in both x- and y-directions.

Both tanks are subjected to the first 20 s of the severe ground shaking recorded at a free-field site near Sylmar County Hospital during the 1994 Northridge, California Earthquake.[15] The acceleration, velocity and displacement time histories of the ground motion are shown in Figure 3. The North–South component was applied in the x-direction and the East–West component was applied in the y-direction (Figure 1(c)).

Response time histories

Shown in Figure 4(a) are the time histories of the x-component of the impulsive overturning moment $M_{ix} = -\,m_i h_i(\ddot{u}_{ix} + \ddot{x}_g)$. The values for the fixed-base tank are shown in dashed lines while those for the isolated tank are shown in solid lines. The results on the left are for the broad tank and those on the right are for the slender tank. The period of the isolated broad and slender tank is about 2·2 and 2·5 s, respectively. These values are several times greater than the fixed-base impulsive period of 0·25 s for broad and 0.16 s for slender tank, and lower than the convective period of 8·1 s for broad and 3·7 s for slender tank. For isolation to be effective, the period of the isolated system should be longer than the fixed-base impulsive period yet not

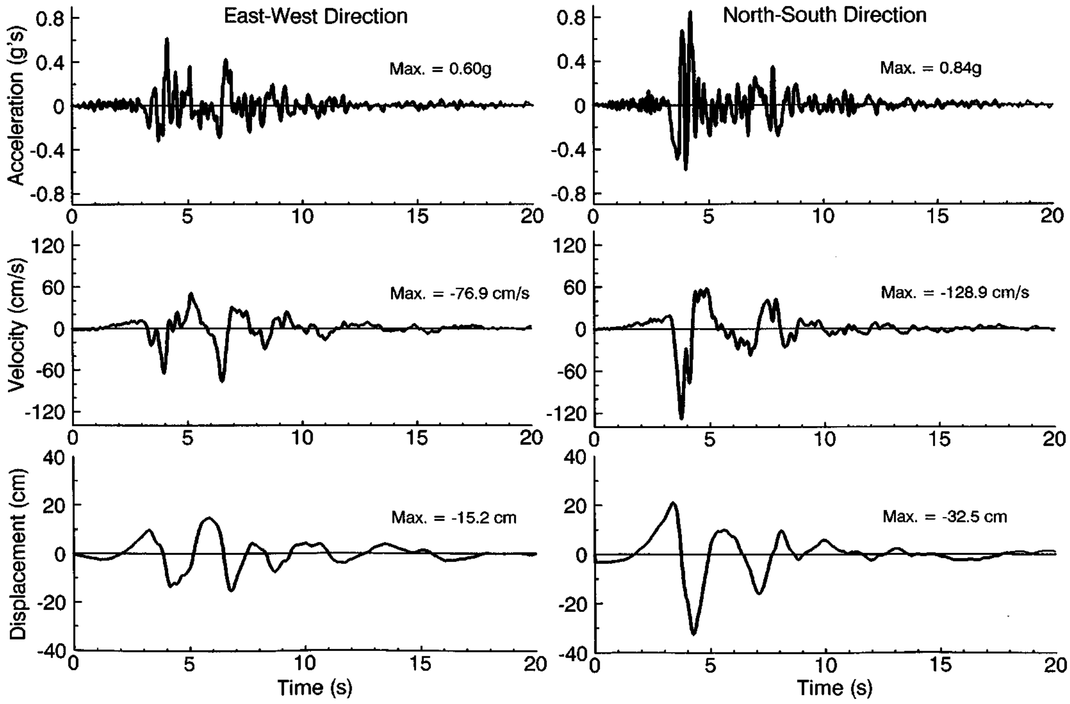

Figure 3. 1994 Northridge, California Earthquake ground motion records from Sylmar County Hospital free-field site[15]

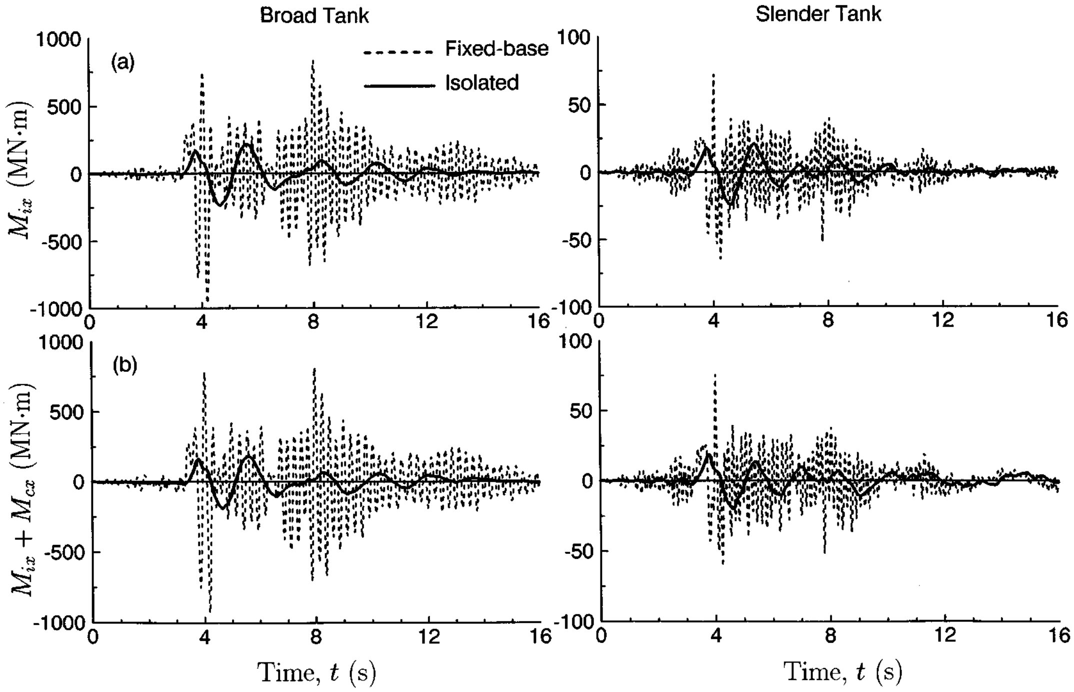

Figure 4. Time histories of: (a) Impulsive overturning base moment, and (b) total (impulsive plus convective) overturning base moment for fixed-base and isolated tanks

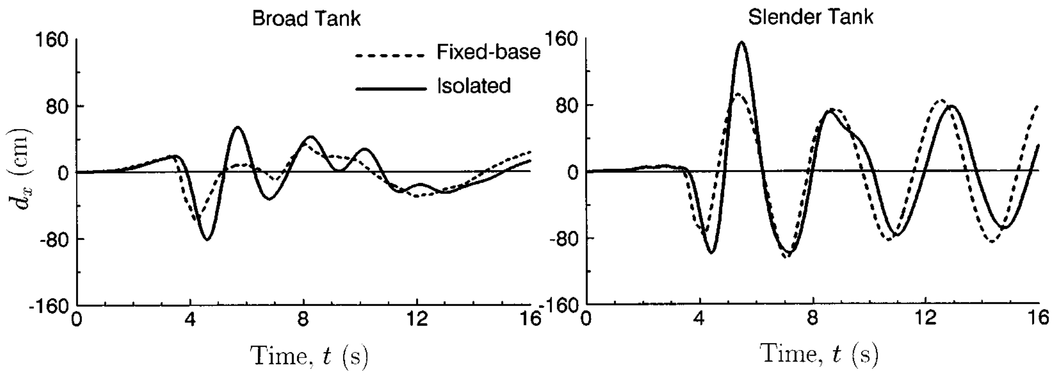

Figure 5. Time histories of vertical displacement due to free-surface sloshing in fixed-base and isolated tanks

close to the convective period. Base isolation reduces the resultant impulsive moment $\sqrt{M_{ix}^2 + M_{iy}^2}$ by nearly 74 per cent for the broad tank and 65 per cent for the slender tank.

The convective response, which is sensitive to long period content of base motion, is expected to increase as a result of isolation. The plots in Figure 4(b) are for the net overturning moment in x-direction, obtained by adding the convective moment $M_{cx} = -m_c h_c(\ddot{u}_{cx} + \ddot{x}_g)$ to the impulsive moment M_{ix}. Note that for both fixed-base tanks the convective action does not contribute significantly to the overturning moment. Despite an increase in the period due to isolation, the increase in the convective moment is negligible for both tanks. Similar observation was made by Chalhoub and Kelly[16] in their study of tanks in base isolated buildings. The resultant overturning moment $\sqrt{(M_{ix} + M_{cx})^2 + (M_{iy} + M_{cy})^2}$ has a maximum value of 932 MN m for the fixed-base and 197 MN m for the isolated broad tank. The corresponding values for the slender tank are 76 and 21 MN m, respectively.

The maximum value of the axial compressive stress in the wall of the fixed-base tanks, computed from ordinary beam theory, is 17 MPa for the broad and 67 MPa for the slender tank. The value for the fixed-base slender tank is about 30 per cent higher than that allowed by the API Standard 650[17] to guard against buckling damage. As a result of isolation, the axial compressive stress reduces to 3.6 MPa for the broad and 19 MPa for the slender tank; these values are significantly lower than the allowable values.

Shown in Figure 5 are the plots of the maximum vertical displacement of the liquid surface at $\phi = 0°$ (Figure 1(c)), computed from:[9]

$$d_x = 0{\cdot}837R\frac{A_{cx}}{g} \tag{2}$$

where $A_{cx} = \omega_c^2(u_{cx} - u_{bx})$ is convective pseudo-acceleration in the x-direction; and g the acceleration due to gravity. As a result of isolation, the free-surface displacement increases by 40 per cent for the broad and 47 per cent for the slender tank.

Shown in Figure 6 are the plots of the axial tensile force in a bearing located at $\phi = 0°$ (Figure 1(c)), computed from:

$$V_{bx} = \frac{2(M_{ix} + M_{cx})}{nR} - \frac{W + m_b g}{n} \tag{3}$$

where n is the total number of bearings (60 for broad and 12 for slender tank). Since, the dead weight supported by the bearings is small compared to the impulsive liquid weight, the bearings experience a net tensile force due to overturning moment. As expected, the tensile force is higher for the slender tank. The maximum tensile force experienced by any bearing is 200 kN for the broad tank, and 560 kN for the slender

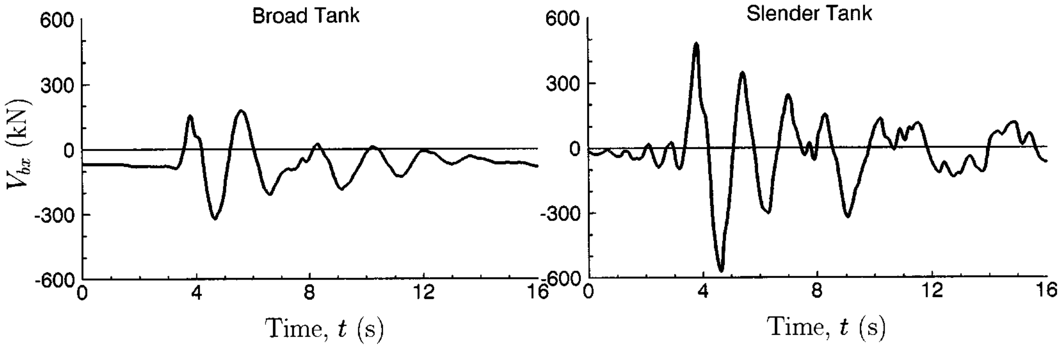

Figure 6. Time histories of tensile force in the bearing located at $\phi = 0°$ (Figure 1c)

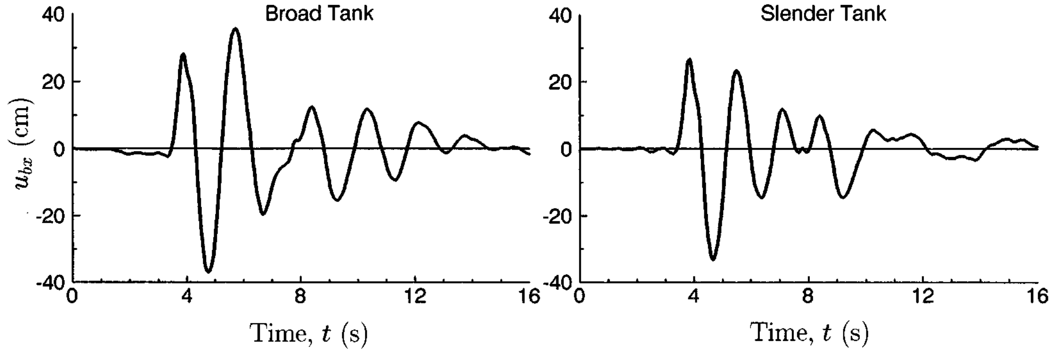

Figure 7. Time histories of horizontal deformation of the bearings in x-direction

tank. This amounts to a tensile stress of 1·45 MPa for a 70 cm diameter bearing in the slender tank. Test results have shown that bearings with bolted connections can withstand an even higher tensile stress.[18] If a concrete ring beam is used at the base, the increased precompression due to the weight of the beam and that of the liquid supported by it will reduce the tensile stress in the bearings.

The plots in Figure 7 are for the bearing deformation u_{bx} for the two isolated tanks. The resultant deformation $\sqrt{u_{bx}^2 + u_{by}^2}$ has a maximum value of 39 cm for the broad and 35 cm for the slender tank; this will have to be taken into account in the design of the flexible membrane between the wall and the base plate. The attached piping may be routed through the bottom of the tank to eliminate the need for accommodating the bearing deformation.

Shown in Figure 8 are the relationships between the bearing deformation u_{bx} and the base shear F_{bx} (equation 1(c)). The area enclosed between a force–deformation loop represents the energy lost in a vibration cycle. The equivalent viscous damping computed from the size of the largest loop (Reference 19, pp. 94–100) is about 17·5 per cent for the broad tank and 16 per cent for the slender tank.

Effect of vertical ground motion

Since the bearings are stiff axially, the tank is not isolated in the vertical direction. Large hydrodynamic pressures that are uniform in the circumferential direction may therefore develop due to vertical shaking.[9] This, in turn, increases the 'effective' height of the liquid supported by the membrane. The magnitude of the hydrodynamic pressures will depend upon the flexibility of the membrane and that of the tank wall. This

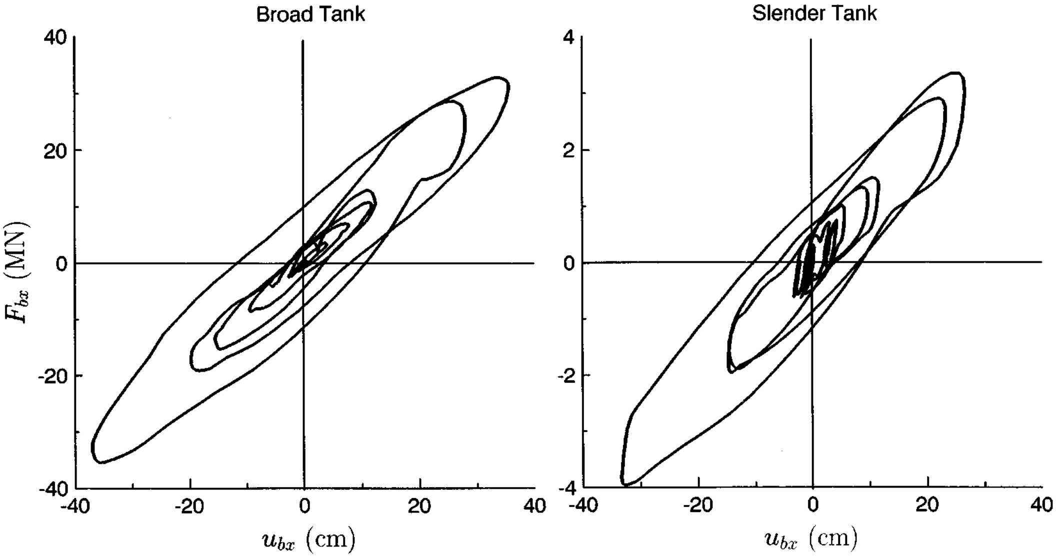

Figure 8. Relationships between the base shear and bearing deformation in x-direction

needs to be investigated further. For fixed-base tanks, the hoop stress in the tank wall due to vertical shaking is usually unimportant compared to the axial compressive stress; for isolated tanks, the hoop stress may become relatively important.

CONCLUSION

Seismic base isolation of cylindrical, ground-supported, liquid-storage, steel tanks has been proposed by disconnecting the wall of the tank from the base plate and supporting it on a ring of horizontally flexible bearings; the base plate is supported directly on the ground. The gap between the wall and the base plate is closed with a flexible membrane which allows the wall to move freely in the horizontal direction. It is seen that isolation reduces dramatically the values of hydrodynamic base shears, overturning moments, and the axial compressive stresses in the tank without a significant increase in free-surface sloshing. Since the dead weight supported by the bearings is small compared to the total liquid weight, the bearings in slender tanks experience a net tensile force during strong ground shaking. The cost saving in the foundation, base anchorage, horizontal restraint, and the tank material is likely to offset significantly the additional cost of the isolation bearings, flexible membrane, and the base stiffener.

APPENDIX

Notation

A_{cx}	$\omega_c^2(u_{cx} - u_{bx})$ = pseudo-acceleration of convective mass in x-direction
d_x	maximum vertical displacement of liquid-surface due to excitation in x-direction
F_{bx}	x-component of horizontal force in isolation system
g	acceleration due to gravity
h_c	height of the centroid of convective hydrodynamic wall pressures
h_i	height of the centroid of impulsive hydrodynamic wall pressures
H	height of liquid in tank

m_b	mass of base stiffener
m_c	mass of convective liquid
m_i	mass of impulsive liquid
M_{cx}	convective overturning moment due to excitation in x-direction
M_{ix}	impulsive overturning moment due to excitation in x-direction
n	total number of bearings
R	radius of tank wall
u_{bx}	deformation of bearings in x-direction
u_{cx}	x-component of horizontal displacement of convective mass relative to ground
u_{ix}	x-component of horizontal displacement of impulsive mass relative to ground
V_{bx}	tensile force in bearing at $\phi = 0°$ due to excitation in x-direction
W	weight of tank wall
$\ddot{x}_g$	ground acceleration in x-direction
$\ddot{y}_g$	ground acceleration in y-direction
ω_c	fixed-base convective frequency (rad/s)
ω_i	fixed-base impulsive frequency (rad/s)
ζ_c	fixed-base convective damping ratio
ζ_i	fixed-base impulsive damping ratio

REFERENCES

1. R. D. Hanson, 'Behavior of liquid storage tanks, the Great Alaska earthquake of 1964', *National Academy of Sciences*, Washington, DC, **7**, 331–339 (1977).
2. G. C. Manos and R. W. Clough, 'Tank damage during the May 1983 Coalinga earthquake', *Earthquake Engng. Struct. Dyn.*, **13**(4), 449–466 (1985).
3. P. K. Malhotra and A. S. Veletsos, 'Seismic response of unanchored and partially anchored liquid-storage tanks', *TR*-105809, Electric Power Research Institute (EPRI), Palo Alto, CA, 1995.
4. R. W. Miles, 'Practical design of earthquake-resistant steel reservoirs', *Proc. tech. councils on lifeline earthquake engrg., specialty conf.*, ASCE, New York, NY, 1977, pp. 168–182.
5. T. E. Kelly and R. L. Mayes, 'Seismic isolation of storage tanks', *Proc. Sessions Related to Seismic Engrg. at Structures Congress '89,* C. A. Kircher and A. K. Chopra (Eds), ASCE, New York, NY, 1989, pp. 408–417.
6. F. E. Tajirian, 'Seismic isolation of critical components and tanks', *Proc. ATC-17-1 seminar on seismic isolation, passive energy dissipation, and active control*, San Francisco, CA, **1**, 233–244 (1993).
7. V. A. Zayas and D. S. Low, 'Application of seismic isolation to industrial tanks', *Proc. pressure vessels and piping conf.*, ASME/JSME, Hawaii, PVP-Vol **319**, 273–286 (1995).
8. P. K. Malhotra, 'Method for seismic base isolation of liquid-storage tanks', *J. struct. eng.* ASCE **123**(1), 113–116 (1997).
9. A. S. Veletsos, 'Seismic response and design of liquid storage tanks', *Guideline for the Seismic Design of Oil and Gas Pipeline Systems, Tech. Councils on Lifeline Earthquake Engrg.*, ASCE, New York, NY, 1984, pp. 255–370, 443–461.
10. M. A. Haroun and G. W. Housner, 'Seismic design of liquid-storage tanks', *J. tech. councils* ASCE **107**(1), 191–207 (1981).
11. A. S. Veletsos and Y. Tang, 'Soil–structure interaction effects for laterally excited liquid-storage tanks', *Earthquake Engng. Struct. Dyn.*, **19**(4), 473–496 (1990).
12. A. S. Veletsos, P. Shivakumar, Y. Tang and H. T. Tang, 'Seismic response of anchored steel tanks', *Proc. 3rd symp. on current issues related to nuclear power plant struct., equip., and piping*, A. J. Gupta (ed.), North Carolina State Univ., NC, X/2-2–15 (1990).
13. S. Nagarajaiah, A. M. Reinhorn and M. C. Constantinou, '3D-BASIS: Nonlinear dynamic analysis of three-dimensional base isolated structures: Part II', *NCEER 91-0005*, National Ctr. for Earthquake Engrg. Res., State Univ. of New York, Buffalo, NY, 1991.
14. P. C. Tsopelas, S. Nagarajaiah, M. C. Constantinou and A. M. Reinhorn, '3D-BASIS-M: Nonlinear dynamic analysis of multiple building base isolated structures', *NCEER 91-0014*, National Ctr. for Earthquake Engrg. Res., State Univ. of New York, Buffalo, NY, 1991.
15. R. Darragh, T. Cao, C. Cramer, M. Huang and A. Shakal, 'Processed CSMIP strong-motion records from the Northridge, California Earthquake of January 17, 1994: Release 1', *OSMS 94-06A*, Calif. Strong Motion Instrumentation Prog., Sacramento, CA, 1994.
16. M. S. Chalhoub and J. M. Kelly, 'Theoretical and experimental studies of cylindrical water tanks in base isolated structures', *EERC 88-07*, Earthquake Engrg. Res. Ctr., Univ. of Calif., Berkeley, CA, 1988.
17. 'Welded steel tanks for oil storage', *API Standard 650*, 8th Ed., American Petroleum Institute (API), Washington, DC, 1988.
18. R. G. Tyler, 'Rubber bearings in base-isolated structures—a summary paper', *Bull. New Zealand national soc. earthquake eng.* **24**(3), 251–274 (1991).
19. A. K. Chopra, *Dynamics of Structures: Theory and Applications to Earthquake Engineering*, Prentice-Hall, Englewood Cliffs, NJ, 1995.